Status and recent results of the South Pole Acoustic Test Setup

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Abstract

The South Pole Acoustic Test Setup (SPATS) has been deployed to study the feasibility of acoustic neutrino detection in Antarctic ice around the South Pole. An array of four strings equipped with acoustic receivers and transmitters, permanently installed in the upper 500 m of boreholes drilled for the IceCube neutrino observatory, and a retrievable transmitter that can be used in the water filled holes before the installation of the IceCube optical strings are used to measure the ice acoustic properties. These include the sound speed and its depth dependence, the attenuation length, the noise level, and the rate and nature of transient background sources in the relevant frequency range from 10 kHz to 100 kHz. SPATS is operating successfully since January 2007 and has been able to either measure or constrain all parameters. We present the latest results of SPATS and discuss their implications for future acoustic neutrino detection activities in Antarctica.

Keywords: Acoustic neutrino detection, Acoustic ice properties, SPATS
PACS: 43.50.+y, 43.58.+z, 93.30.Ca

1. Introduction

The origin and acceleration of cosmic rays to energies beyond 10^{20} eV is one of the big open questions in astroparticle physics today. Carrying electric charge, cosmic rays are deflected in magnetic fields during their propagation and possibly do not point back to their source. However, the cosmic rays being hadrons, interactions in matter or photon fields at the source should produce high energy neutrinos that would arrive at earth undeflected and their energy spectrum will carry valuable information of the physics processes at their source. For a recent review see e.g. Ref. [1]. If the cosmic rays at the highest energies observed are protons, there additionally is the "guaranteed flux" of cosmogenic neutrinos, produced in the interaction of cosmic rays with energies above approx. 10^{19} eV with the cosmic microwave background radiation [2, 3]. Measuring the energy spectrum of cosmogenic neutrinos will allow one to study different models of cosmological source evolution. Neutrinos at ultra high energies are also a valuable tool to study the neutrino-nucleon cross section at high center of mass energies.

The detection of the small neutrino flux predicted at the highest energies ($E > 10^{17}$ eV) requires detector target masses of the order of 100 gigatons, corresponding to 100 km^3 of water or ice. The optical Cherenkov neutrino detection technique, currently employed in experiments like IceCube, ANTARES, or Baikal, is not easily scalable from 1 km^3-scale telescopes to such large volumes. Promising techniques, with longer signal attenuation lengths, allowing for the sparse instrumentation of large natural targets like Antarctic ice, are the radio and acoustic detection methods. The radio approach utilizes the Askaryan effect, the coherent emission of radio waves from the charge asymmetry developing in an electromagnetic cascade in a dense medium [4]. Acoustic detection is based on the thermo-acoustic sound emission from a particle cascade depositing its energy in a very localized volume causing sudden expansion that propagates as a shock wave perpendicular to the cascade [5].

Experiments utilizing the radio technique, the RICE experiment at South Pole [6] being co-deployed with IceCubes predecessor AMANDA, and the balloon borne ANITA experiment [7] currently deliver the most stringent upper limits on the cosmogenic neutrino flux.

The South Pole Acoustic Test Setup has been designed to study the feasibility of acoustic neutrino detection at the South Pole by measuring the acoustic properties of the ice in the frequency range of interest from 10 kHz to 100 kHz. These parameters include:

- The speed of sound and its variation with depth. A gradient in the speed of sound depth profile leads to refraction during the propagation of acoustic signals over large distances and makes the reconstruction of the position of the source more difficult and can lead to multiple solutions.
- The attenuation length and its frequency dependence. This will be one of the drivers for the geometry of a future acoustic neutrino telescope, determining,

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together with the noise level, the required spacing between sensors for a given lower energy threshold. Frequency dependent attenuation will lead to a variation of the expected acoustic signal shape with distance.

- The absolute noise level. Residual acoustic noise in the ice will be the other main quantity to determine the energy threshold. Its stability with time is important to be able to operate a detector with fixed trigger settings.
- Characterization of any sources of impulsive noise, which might be misinterpreted as neutrino signals. To enhance the signal to noise ratio it is essential to have a good description of the temporal and spatial distribution of transient signals in the ice.

Measurement of all these parameters will allow us to get a realistic sensitivity estimate for a possible future acoustic neutrino telescope in Antarctic ice.

2. Detector setup and data taking

To measure the acoustic properties of the ice at the geographic South Pole a system of four instrumented vertical lines, called *strings* A, B, C, and D, have been installed in boreholes of the IceCube neutrino telescope after deployment of the IceCube optical modules. Each string holds seven *stages*, a combination of an acoustic *sensor* and *transmitter* separated by a distance of approx. 1 m. The horizontal distances between strings range from 125 m (which is the spacing between IceCube strings) to 543 m. Vertically the depth range from 80 m to 500 m has been instrumented with increasing spacing of sensors in the deeper ice to be able to sample the transition from the firn[1] region to the bulk ice. Figure 1 schematically shows the configuration of SPATS and the depth distribution of the acoustic stages. Strings A to C have been deployed in January 2007, string D with improved sensors and transmitters and reaching deeper to 500 m has been installed one year later in December 2007.

The SPATS sensors consist of a cylindrical stainless steel pressure housing with a diameter of 10 cm in which three piezoelectric elements are mounted to the wall, separated by 120 degrees to get full azimuthal coverage. A three-stage low noise pre-amplifier with a gain of 10^4 is attached directly to the piezoelectric element and the analogue signal is transmitted to the surface on a shielded twisted pair cable. The transmitters are comprised of a high voltage pulse generator protected in a steel housing that drives a ring shaped piezoelectric element casted in epoxy for protection and mounted below the housing. The high voltage generator produces pulses with an amplitude of up to 1.5 kV and a length of 17 μs. For string D the experience gained during the first year of SPATS operation has been used to improve sensors and transmitters. In the string D sensors a central metal post that was used to press the piezoelectric elements to the housing wall was removed and all piezoelectric elements are now mounted to the wall individually. This has reduced mechanical coupling and sound transfer between the three individual channels. Further, on string D at a depth of 190 m and 430 m an alternative type of sensor, HADES (Hydrophone for Acoustic Detection at South Pole), has been deployed. For the HADES sensors the piezoelectric element and pre-amplifier have been moved out of the steel housing and have been cast in resin and mounted below the housing, similar to the transmitters. This allows us to study acoustic signals with different systematics introduced by the sensor. The string D transmitters have an optimized high voltage circuit design which allows for longer duration pulses with higher amplitudes.

On the surface, buried in a read-out box in the snow above each string, an industrial PC, called string-PC, is placed that is used for digitization, time stamping, and storage of the data. Each string-PC is connected by a symmetric DSL connection to the SPATS master-PC that is housed in the IceCube laboratory at South Pole station. The master-PC collects the data from all four string-PCs, distributes a GPS timing signal to them, and prepares the data for transfer to the northern hemisphere via satellite or tape storage. SPATS is operated in different data taking modes. Of each hour, 45 minutes are used for transient data taking with three channels of each string, using a simple single channel threshold trigger. On each trigger signal 5 ms of data are recorded with a sampling rate of 200 kHz centered around the triggering sample. The remaining 15 minutes are used for recording environmental and system health monitoring data. This includes monitoring of the acoustic noise floor for which each sensor channel records 100 ms of untriggered data at 200 kHz sampling rate. SPATS is described in detail in Ref. [8].

To increase flexibility in data taking as well as the range of available transmitter-receiver distances a retrievable transmitter, called *pinger* has been developed. While constantly emitting acoustic pulses, it is lowered into the water filled IceCube boreholes, stopped for five minutes at the SPATS instrumented depths, and removed before installation of the IceCube optical modules. The pinger has been deployed in six holes in 2007/2008 where it was operated with broad band (approx. 15 kHz to 30 kHz) pulses repeated at 1 Hz. The obtained data led to the measurement of the speed of sound depth profile. In the following IceCube drilling season it was used in four holes with major technical improvements. Mechanical centralizers were installed to prevent the pinger from swinging in the hole and thus stabilize the waveforms. The emitted pulse type was kept the same, but with an increased repetition rate of 10 Hz. These modifications, as well as the more favorable

[1]The transition region from a more loose snow/air mixture at the surface to solid ice is called firn. It has a width of 150 m to 200 m.

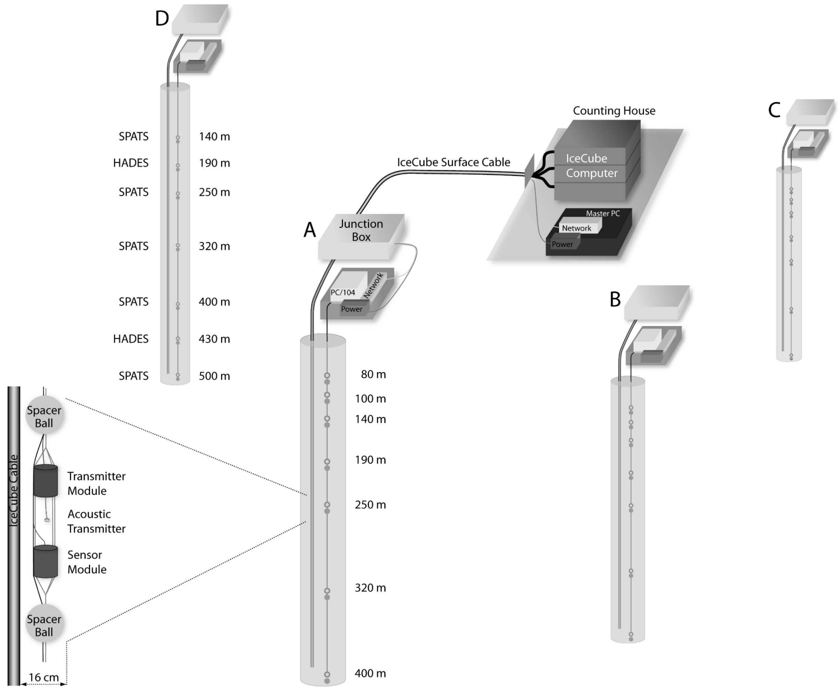

Figure 1: Schematic of SPATS detector setup deployed in IceCube boreholes at the South Pole.

positions of the IceCube holes being drilled with respect to the SPATS array, led to the determination of the attenuation length. In 2009/2010 the pinger was modified to emit lower bandwidth pulses at three well defined frequencies (30, 45, and 60 kHz) and deployed in three boreholes, also going to deeper depths, down to 1000 m. The measured data is used to study the frequency dependence of the attenuation length, as well as the speed of sound on inclined paths.

3. Results

3.1. Speed of sound

We determined the speed of sound on horizontal paths of 125 m length for all SPATS instrumented depths from 80 m down to 500 m from the 2007/2008 pinger data. The pinger emission is time-synchronized to a GPS clock which allows for a precise measurement of the propagation time from the pinger to the SPATS sensors. In addition to the sound speed profile for longitudinal acoustic waves (p-waves), also a profile for transverse waves (s-waves) could be measured. While p-waves are produced directly by the pinger in the water filled IceCube borehole, the s-waves, which cannot propagate in water, are generated at the water-ice interface from p-waves with non-normal angle of incidence.

In the top 200 m of the ice shield, the firn region, a strong sound speed gradient is observed, that is consistent with previous data. Below the firn our measurement is the first one for p-waves in this depth region, and the first in-situ measurement for s-waves. The resulting sound speed gradient g is compatible with zero, implying that sound waves propagate without refraction below a depth of 200 m [9]:

$$\begin{aligned} v_p(375\text{ m}) &= (3878 \pm 12)\ \mathrm{m\,s^{-1}} \\ g_p &= (0.087 \pm 0.13)\ \mathrm{m\,s^{-1}\ m^{-1}} \\ v_s(375\text{ m}) &= (1975.8 \pm 8.0)\ \mathrm{m\,s^{-1}} \\ g_s &= (0.067 \pm 0.086)\ \mathrm{m\,s^{-1}\ m^{-1}} \end{aligned}$$

The largest uncertainty in the measurement results from the determination of the horizontal distance between emitter and receiver.

The data obtained in the 2009/2010 season with the pinger being deployed to a depth of 1000 m will enable us to additionally measure the speed of sound on inclined paths. This will allow us to probe the fabric of the ice: if there is a preferred crystal orientation in South Pole ice the measured speed of sound will vary depending on the direction. For single crystal ice the sound speeds along and perpendicular to the crystals c axis differ by 4% [10] which can be resolved with the precision achievable with SPATS.

3.2. Attenuation length

Measuring the attenuation length requires the comparison of signal amplitudes or energies after different propagation lengths through the ice. To achieve this, the 2008/2009 pinger was optimized by mechanical centralizers to prevent it from swinging during deployment, reducing pulse to pulse variations caused by different signal transmission

characteristics at the water-ice interface, by using IceCube holes that were aligned with respect to the SPATS array, thus reducing the systematic uncertainties due to variations in the azimuthal response function of our receivers, and by higher emission rates (10 Hz instead of 1 Hz) to improve the signal to noise ratio.

We analyzed data sets using different sound sources – the pinger, the frozen-in SPATS transmitters, and transient signals from freezing IceCube holes – to determine the attenuation length. To minimize the uncertainties due to different sensitivity of the sensors and unknown angular response, the attenuation length was determined with each sensor individually placing the sound source at different distances to the receiver, while trying to keep the same direction seen from the sensor. All methods consistently deliver an attenuation length of about 300 m with a 20% uncertainty [11]. The error represents the spread between attenuation lengths measured with each sensor. This result is in strong contradiction with the phenomenological model prediction of (9 ± 3) km with absorption as the dominant mechanism and negligible scattering on ice grains [12].

To investigate this discrepancy the pinger has been modified for the 2009/2010 Pole season to allow us to measure the attenuation length at different frequencies f from 30 kHz to 60 kHz. The result will help to discriminate between different attenuation mechanisms contributing: the scattering coefficient is expected to increase with f^4 while the absorption coefficient should be nearly frequency independent. The modified pinger has successfully been deployed in three IceCube holes aligned with respect to the SPATS array at horizontal distances between 180 m and 820 m and delivered high quality data which is currently being analyzed.

To illustrate the impact of the shorter-than-expected attenuation length on acoustic neutrino detection at South Pole let us assume a simple model for the peak pressure $p_\perp(d)$ in the distance d perpendicular to the center of the axis of a cascade of energy $E_{\rm casc}$. This model approximately reproduces the more detailed calculations presented for example in [13]:

$$p_\perp(d) = 30\ \mathrm{mPa} \cdot \frac{E_{\rm casc}}{10^{18}\ \mathrm{eV}} \frac{100\ \mathrm{m}}{d}\, e^{-(d-100\,\mathrm{m})/\lambda}$$

where λ is the attenuation length. Figure 2 shows $p_\perp(d)$ for two different cascade energies and different attenuation lengths together with a trigger threshold of a future hypothetical neutrino telescope of 10 mPa. It can be seen that for an energy of 10^{18} eV, close to the lower energy threshold where the largest part of the neutrino flux is expected for e.g. cosmogenic neutrinos, the pulse amplitude decrease is dominated by the $1/d$ geometric term and the loss in "visible range" is only a factor of 1.5 from no attenuation to 300 m attenuation length. Only for significantly higher energies attenuation becomes the dominant loss mechanism, but at these high energies neutrino signals still can be detected over very large distances.

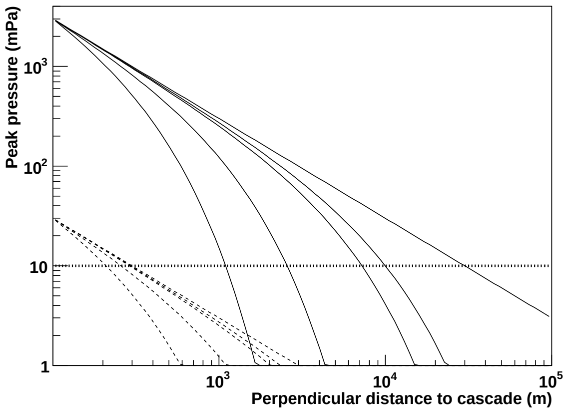

Figure 2: Neutrino signal peak pressure at different perpendicular distances to the cascade using a simple model. The solid lines correspond to a cascade energy of 10^{20} eV, the dashed lines correspond to a cascade energy of 10^{18} eV. The five lines in each set illustrate different attenuation lengths (top to bottom: infinity, 9 km, 5 km, 1 km, 300 m). A hypothetical trigger threshold of 10 mPa is indicated. For low energies the loss in "visibility range" due to an attenuation length of 300 m is only about a factor of 1.5 compared to no attenuation.

3.3. Absolute noise level

The high stability of the noise level over time [14] makes Antarctic ice a favorable medium compared to (sea) water. However, the measurement of the absolute noise level, i.e. the acoustic pressure incident on the sensor, turns out to be one the most persistent problems within the SPATS project.

The electric noise signal measured at the input of the ADC is a superposition of electronic self noise of the sensor, electromagnetic interference picked up during the analogue data transmission from the sensor to the surface over a twisted pair connection, and possible acoustic noise contributions in the ice. While all SPATS sensors have been calibrated in the lab in water at 0°C before deployment, it is not at all clear that their sensitivity will remain the same in South Pole ice at temperatures of −50°C, increased static pressure, and the different acoustic impedance matching at the ice-sensor, as compared to the water-sensor, interface. While the lack of a standardized sound source for ice makes in situ calibration of the sensors impossible, the influence of the different environmental effects on the sensitivity can be studied separately in the lab [15]. The sensitivity of an exemplary SPATS sensor in air increased by a factor of 1.5 ± 0.2 when cooled down to −50°C. For the same sensor, no systematic change with ambient pressure (in water at room temperature) was observed in the range up to 100 bar. The sensitivity variation due to pressure changes was determined to be less than 30%. The variation of sensor response due to the coupling to a different medium is currently under study in a 3 m^3 block of clear ice produced in a tank of the IceTop air shower array placed in a freezing container.

Due to the unknown correlation between the different

environmental effects when exposing the sensor to a combination of all of them in the deep Antarctic ice a measurement of the absolute noise level is currently not possible. We estimate the noise level at South Pole under the assumption that the influence of temperature and static pressure are uncorrelated and thus the in-situ sensitivity is increased by a factor of 1.5 compared to the initial laboratory calibration. To minimize the influence of a possibly modified frequency response due to the different acoustic coupling we will not use the sensor's full frequency dependent response, but will use a mean sensitivity of 2.8 V/Pa before any corrections, averaged over all sensor channels and over the relevant frequency range $f < 50$ kHz. Integrating the noise power spectrum of each sensor from 0 to 50 kHz and dividing by the mean sensitivity times the factor of 1.5 correcting for the temperature yields a noise level for each channel. Figure 3 shows the resulting noise level as function of sensor depth; the error bars indicate the spread between the up to 12 sensor channels deployed at each depth. Also indicated is the 7 mPa mean equivalent self noise measured in the lab prior to deployment. Quadratic subtraction of the equivalent self noise yields a residual noise that is a superposition of acoustic noise, electronic noise, and electromagnetic interference. We also show the values derived for the two HADES sensors which are unfortunately dominated by electronic self noise.

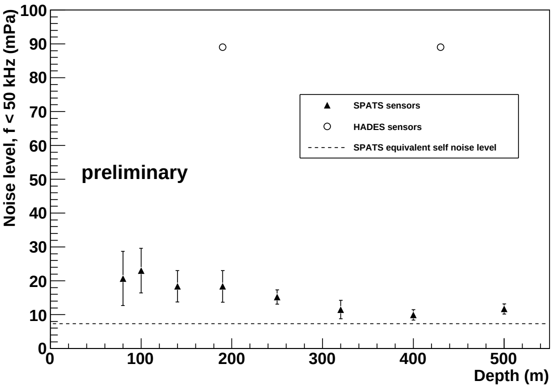

Figure 3: Estimated acoustic noise level at the SPATS instrumented depths (see text for details) and mean equivalent self noise measured in the lab prior to deployment. The error bars represent the spread between different sensor channels. The two HADES sensors are dominated by electronic self noise.

To obtain a more reliable measurement of the absolute noise level, including sensitivity variations induced by the coupling of the sensor to the ice, we plan to deploy two new sensors during the 2010/2011 austral summer. These sensors are equipped with an acoustic transmitter built into the steel housing, exciting the sensor in a well defined manner independent of the medium outside. Comparing signals generated with this transmitter with the sensor being in air, water, or ice will allow us to follow the evolution of response from deployment until equilibrium with the bulk ice is reached.

3.4. Transient noise sources

In transient data taking mode three channels on each SPATS string record triggered data. Above-threshold events in each single channel are written to disk with a typical trigger rate of 0.1 Hz per channel, a data set that is dominated by single bin excesses from the tail of the Gaussian noise distribution. A search for coincidences in time is performed offline with a coincidence window of 200 ms corresponding to the longest distance across the SPATS array of approx. 775 m. The vertex of transient events producing triggers on all four strings is reconstructed using an idealized global positioning system algorithm. The horizontal positions of all reconstructed vertices are shown in Fig. 4.

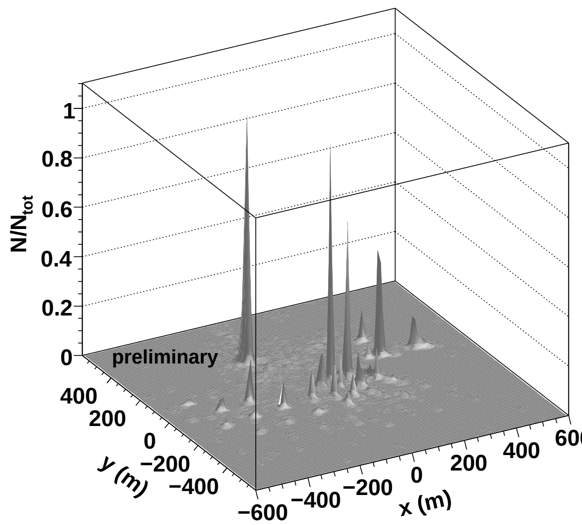

Figure 4: Normalized horizontal distribution of all transient event vertices recorded since August 2008. The vertices are well localized on the horizontal plane. All observed events originate from either the Rodriguez Wells, large caverns melted in the ice for water storage during IceCube drilling, or are emitted from the re-freezing IceCube holes.

All sources of transient noise are well localized in space and have been identified as being man made:

- IceCube boreholes re-freezing after the deployment of the optical module produce cracking noise for a period of about 20 days after which they quiet down again.
- Rodriguez Wells are caverns melted into the ice at a depth of 50 m to 100 m as a water storage reservoir during IceCube drilling. With the relocation of the drill camp each austral summer a new Rodriguez Well is created and the old wells, with an unknown amount of residual water inside, are abandoned to re-freeze.

The absence of any transient events observed from locations other than known sources allows us to set a limit

on the flux of ultra high energy ($E_\nu > 10^{20}$ eV) neutrinos. Details on transient noise in SPATS and the neutrino flux limit are presented at this conference in Ref. [16].

To be able to operate SPATS with lower trigger thresholds – the current threshold is set to limit the data volume to the allocated bandwidth for satellite data transfer from South Pole – a new data acquisition software framework has been developed and is currently being tested in SPATS. This will allow us to have online communication between the string-PCs and the master-PC and search online for coincidences of acoustic signals in time, reducing the data volume being stored.

4. Future plans

The ice acoustic properties measured by SPATS allow us to study the feasibility of acoustic neutrino detection in Antarctic ice. If our estimations of the absolute noise level are verified by the planned measurement, the unexpectedly short attenuation length can be compensated for by glaciophones with low self noise measuring signals at the limit of acoustic background noise.

Due to the low expected neutrino flux at ultra high energies and the absence of a natural calibration source, like atmospheric muons and neutrinos are for optical Cherenkov neutrino telescopes, good background rejection will be an important topic for a future UHE neutrino detector. One possibility to achieve is hybrid detection with at least two different, independent detection systems, reducing systematic uncertainties and allowing for cross calibration. Two techniques aiming at large, sparsely instrumented detectors are radio and acoustic neutrino detection. Both approaches currently favor instrumentation with a typical horizontal spacing of the order of one kilometer, which suggests common deployments. While for the radio Cherenkov cone signature shallow deployments of antennas seem sufficient, for the acoustic pancake-shaped signal pattern deeper sensors (down to a few hundred meters) improve the sensitivity to neutrinos significantly.

The radio detection method intrinsically has a lower energy threshold than the acoustic technique. However, due to the very low acoustic transient noise background, at neutrino energies of the order of 10^{17} eV, below the threshold for acoustic neutrino detection, the trigger from the radio detector could be used to read out all acoustic sensors. A single pulse in one of the acoustic sensors in temporal coincidence with the radio signal already can add valuable information to the significance of the detection. At energies above approx. 10^{18} eV a standalone acoustic multiplicity trigger may be feasible.

Simulations of different hybrid radio-acoustic detector arrays [17] show that for an array of strings deployed on a quadratic grid with 500 m spacing covering an area of 25 km^2 and deploying several radio antennas and acoustic sensors to a depth of 300 m, between three and ten percent (depending on the acoustic emission model used) of all neutrino events triggering the radio detector will also produce detectable signal in at least one acoustic sensor. Figure 5 shows the number of simulated events per energy bin triggering the radio detector and generating a detectable signal in at least one acoustic sensor for different sound emission models. Such an array would lead to the hybrid detection of the order of one cosmogenic neutrino per year, assuming the standard ESS neutrino flux [3].

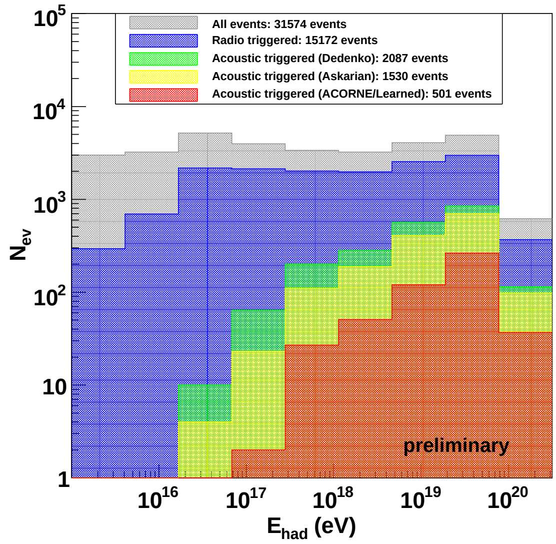

Figure 5: Number of triggered events in a 25 km^2 radio-acoustic array (see text for details) detected by radio only and producing a detectable signal in at least one acoustic sensor for three different models of sound emission (from [17]).

Two large in-ice radio projects are currently pursued in Antarctica: the Askaryan Radio Array (ARA) [18] at South Pole and ARIANNA [19] on the Ross ice shelf. We will study the feasibility of possible acoustic additions to these projects or future extensions to them.

5. Conclusions

The South Pole Acoustic Test Setup has been operated very successfully for almost four years now and has nearly completed its task to measure the acoustic properties of South Pole ice relevant for the acoustic detection of ultra high energy neutrinos. The sound speed depth profile has been measured for the first time in the deep ice and for shear waves and has been found to be consistent with a constant sound speed below 200 m depth. This allows us to reconstruct the position of acoustic sources without having refraction effects to be taken into account which might lead to ambiguous solutions. The attenuation length has been found to be smaller than expected but the impact of this result is not considered as a serious problem for future acoustic neutrino detection activities since the distance over which typical signals can be detected is only decreased by a factor of about 1.5. The exact attenuation

mechanism is under study with data from a dedicated measurement using a retrievable transmitter. The ice at South Pole is free of transient noise that can accidentally be misinterpreted as originating from neutrinos. All transient noise observed originates from well localized, man made sources. The absolute noise level turns out to be challenging to measure due to the absence of standardized acoustic sources. Estimates based on reasonable assumptions yield a noise level comparable to the noise in calm sea, but being very stable with time. A new measurement is planned for the 2010/2011 austral summer to considerably reduce the uncertainties on this last unknown, important quantity.

Combining all results we believe that the acoustic neutrino detection technique can be a valuable part in a future large neutrino telescope combining acoustic and radio methods into a hybrid detector.

Acknowledgements

We acknowledge the support from the following agencies: U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, University of Wisconsin Alumni Research Foundation, the Grid Laboratory Of Wisconsin (GLOW) grid infrastructure at the University of Wisconsin – Madison, the Open Science Grid (OSG) grid infrastructure; U.S. Department of Energy, and National Energy Research Scientific Computing Center, the Louisiana Optical Network Initiative (LONI) grid computing resources; National Science and Engineering Research Council of Canada; Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research (BMBF), Deutsche Forschungsgemeinschaft (DFG), Research Department of Plasmas with Complex Interactions (Bochum), Germany; Fund for Scientific Research (FNRS-FWO), FWO Odysseus programme, Flanders Institute to encourage scientific and technological research in industry (IWT), Belgian Federal Science Policy Office (Belspo); University of Oxford, United Kingdom; Marsden Fund, New Zealand; Japan Society for Promotion of Science (JSPS); the Swiss National Science Foundation (SNSF), Switzerland; A. Groß acknowledges support by the EU Marie Curie OIF Program; J. P. Rodrigues acknowledges support by the Capes Foundation, Ministry of Education of Brazil.

References

References

[1] L. A. Anchordoqui, T. Montaruli, In search of extraterrestrial high-energy neutrinos, Annu. Rev. Nucl. Part. Sci. 60 (2010) 129–162. arXiv:0912.1035[astro-ph.HE].

[2] V. S. Berezinsky, G. T. Zatsepin, Cosmic rays at ultra high energies (neutrino?), Phys. Lett. 28B (6) (1969) 423–424.

[3] R. Engel, D. Seckel, T. Stanev, Neutrinos from propagation of ultra-high energy protons, Phys. Rev. D 64 (2001) 093010. arXiv:astro-ph/0101216.

[4] G. A. Askaryan, Excess negative charge of an electron-photon shower and its coherent radio emission, Sov. Phys. JETP 14 (2) (1962) 441–443.

[5] G. A. Askaryan, B. A. Dolgoshein, A. N. Kalinovsky, N. V. Mokhov, Acoustic detection of high energy particle showers in water, Nucl. Inst. Methods 164 (1979) 267–278.

[6] I. Kravchenko, Recent results from the RICE experiment at the South Pole, this issue.

[7] P. W. Gorham, et al., Observational constraints on the ultra-high energy cosmic neutrino flux from the second flight of the ANITA experiment, Phys. Rev. D 82 (2010) 022004. arXiv:1003.2961[astro-ph.HE].

[8] Y. Abdou, et al., Design and performance of the South Pole Acoustic Test Setup, in preparation.

[9] R. Abbasi, et al., Measurement of sound speed vs. depth in South Pole ice for neutrino astronomy, Astropart. Phys. 33 (2010) 277–286. arXiv:0909.2629[astro-ph.IM].

[10] V. F. Petrenko, R. W. Whitworth, Physics of ice, Oxford University Press, 1999.

[11] R. Abbasi, et al., Measurement of acoustic attenuation in South Pole ice, submitted to Astropart. Phys. arXiv:1004.1694[astro-ph.IM].

[12] P. B. Price, Attenuation of acoustic waves in glacial ice and salt domes, J. Geophys. Res. 111 (2006) B02201. arXiv:astro-ph/0506648.

[13] S. Bevan, et al., Study of the acoustic signature of UHE neutrino interactions in water and ice, Nucl. Inst. Methods A 607 (2009) 398–411. arXiv:0903.0949[astro-ph.IM].

[14] T. Karg, Acoustic noise in deep ice and environmental conditions at the South Pole, Nucl. Inst. Methods A 604 (2009) S171–S174. arXiv:0811.1099[astro-ph].

[15] T. Karg, M. Bissok, K. Laihem, B. Semburg, D. Tosi, Sensor development and caibration for acoustic neutrino detection in ice, in: Proceedings of the 31st International Cosmic Ray Conference, 2009. arXiv:0907.3561[astro-ph.IM].

[16] J. Berdermann, Acoustic transient event reconstruction and sensitivity studies with the South Pole Acoustic Test Setup, this issue.

[17] J. Berdermann, M. Carson, R. Nahnhauer, Possible acoustic additions to a radio UHE neutrino detector, IceCube internal note (July 2009).

[18] K. Hoffman, The Askaryan Radio Array, this issue.

[19] S. W. Barwick, ARIANNA: A new concept for UHE neutrino detection, J. Phys.: Conf. Ser. 60 (2007) 276–283. arXiv:astro-ph/0610631.